Observed shift towards earlier spring discharge in the main Alpine rivers

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ACCEPTED to: Science of the Total Environment, SCARCE 2013 Special Issue

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Highlights:

- A comparison of long-term spring discharge timings over the Alps.
- The largest rivers show similar trends and features of decadal variability.
- Analysis of precipitation, and snow-melting data derived from observations.
- Snowmelt timing explains a portion of the discharge's decadal variability.
- Change of precipitation seasonality causes earlier spring discharge.

Abstract:

In this study, we analyse the observed long-term discharge time-series of the Rhine, the Danube, the Rhone and the Po rivers. These rivers are characterised by different seasonal cycles reflecting the diverse climates and morphologies of the Alpine basins. However, despite the intensive and varied water management adopted in the four basins, we found common features in the trend and low-frequency variability of the spring discharge timings. All the discharge time-series display a tendency towards earlier spring peaks of more than two weeks per century. These results can be explained in terms of snowmelt, total precipitation (i.e. the sum of snowfall and rainfall) and rainfall variability. The relative importance of these factors might be different in each basin. However, we show that the change of seasonality of total precipitation plays a major role in the earlier spring runoff over most of the Alps.

Keywords: mountain hydrology, spring, snowmelt, river discharge, precipitation seasonality, water management.

Abbreviations:
RHI-BASL – Rhine River in Basel
DAN-BRAT – Danube River in Bratislava
RHO-BEAU – Rhone River in Beaucaire
PO-PLSC – Po River in Pontelagoscuro
GRDC – Global Runoff Data Center
HISTALP - historical instrumental climatological surface time series of the Greater Alpine Region
CRU – Climate Research Unit data
GRanD - Global Reservoir and Dam database
DJF – winter (December, January and February)
MAM – spring (March, April and June)
MAM-DJF – spring minus winter

1. Introduction

The Alps are often called the “water towers of Europe” due to the large quantity of water that passes through e.g. the Danube, the Rhine, the Po and the Rhone. In this paper we focus on the timing of the spring discharge, which can affect water quality and management (Hänggi and Weingartner 2011, Gunawardhana and Kazama 2012, Vanham 2012), flood risk (Eckhardt and Ulbrich 2003, Wetter et al. 2011, Bard et al. 2012, Dobler et al. 2012), river navigation and water availability (Middelkoop et al. 2001), tourism (Elsasser et Burki 2002, Beniston et al. 2011), energy production (Hänggi 2012), insurance (Beniston 2012) and natural ecosystems (Keller et al. 2005).

Changes in the timing of spring discharges in mountain regions were first investigated in the U.S. In the Western U.S., the shift towards an earlier spring discharge was attributed to an earlier snowmelt caused by the warming trend observed in that region (Aguado et al. 1992, Dettinger and Cayan 1995 Cayan et al. 2001, Pederson et al. 2011). The earlier snowmelt was consistent with the observed trend in the reduced spring snowpack (Mote 2003, Howat and Tulaczyk 2005). The earlier spring discharge was also affected by the increased ratio of liquid to solid precipitation (Moore et al. 2007) and could be used as a proxy for snowmelt timing in many undisturbed basins (Kuntel 2010). However, human modifications of the river basins, such as damming, irrigation and urbanisation, can often play a part in determining the discharge timings (Arrigoni et al. 2010).

A trend in earlier spring discharges timing was observed in the North-Eastern U.S. as well (Hodgkins et al. 2003), in conjunction with a larger proportion of liquid to solid precipitation (Huntington et al. 2004, Knowles et al. 2006). This was also shown to be true for the U.S. as a whole (McCabe and Clark 2005, Clow 2010). Through modelling studies, the increase of rainfall over snowfall and the earlier snowmelt in the U.S. has been attributed to global warming (Hidalgo et al. 2009) and this trend is projected to continue in the future (Stewart 2004, Rauscher et al. 2008).

Similar results are found for other mountainous and snowy regions in the world, such as Canada (Woo and Thorne 2006) and the Nordic countries (Krasovskaia 2002, Kriauciuniene 2012), the Spanish Pyrenees (Lopez-Moreno 2004), the Himalayas (Bookhagen and Burbank 2010), the Japanese Alps

(Yamanaka et al. 2012) and other key mountain regions (Stewart 2009). This will have significant consequences for future water availability for a substantial portion of the global population (Arora and Boer 2001, Barnett et al. 2005).

Regarding the Alpine rivers, severe winter droughts in the Upper Rhine basin and the associated low river waters were relatively rare in the 20th century compared to the last few hundred years (Pfister et al. 2006). This is consistent with the recent increase in the ratio of the winter over the summer discharge of the Rhine river (Hänggi and Weingartner 2011). Many natural streams in the Alps, especially over the Northern flank, display a similar tendency towards a larger winter flow (Birsan et al. 2005, Stahl et al. 2010, Bard et al. 2012). This is compatible with the earlier spring snowmelt and the larger liquid to solid precipitation ratio observed from the 1980s, mainly at altitudes below 1500-2000 m (Beniston 1997, Beniston et al. 2002, Laternser and Schneebeli 2003, Vincent et al. 2007). Long-term analysis for the Po River discharge also suggests an increase of the winter over the summer discharge ratio (Zanchettin et al. 2008). However, none of these observation-based studies explicitly focused on the timing of the spring discharge, with the exception of Bard et al. (2012), who performed the analysis over the last 40 years.

Modelling studies predict a larger winter to summer Rhine discharge ratio related to the earlier snowmelt during the 21th Century in climate change scenarios of increasing greenhouse gases (Middelkoop et al. 2001, Beniston et al. 2003, Linde et al. 2010). Similar results are found for the Rhone (Beniston et al. 2011, Beniston 2012), and in general for most Alpine rivers (Jasper et al. 2004, Zierl and Bugmann 2005 Horton et al. 2006, Gunawardhana and Kazama 2012).

In this study, we present an integrated long-term analysis of the discharge timings for the main Alpine rivers: the Rhine, the Danube, the Rhone and the Po. As in the previously cited studies, we investigate the influence of climate variability on the river discharge timings. In particular, we analyse the effects of precipitation seasonality, of its liquid portion (i.e. rainfall) and of snowmelt timing. We take advantage of a high-resolution gridded dataset of homogenised temperature and total precipitation time-series covering the Alps for the last 2 centuries, and we advance the understanding of the climatic factors that influence spring discharge timing, in terms of the earlier long-term trend and the low-frequency (decadal) variability.

2. Data and Methods

2.1. *River data*

River discharge monthly time-series have been obtained by combining data from different sources, mainly from the Global Runoff Data Center (GRDC, http://www.bafg.de) and from local regional authorities. The measurement sites were selected for the length of the period covered by the observations and their proximity to the Alps.

Figure 1: Alps orography, river basins and measurement site distribution

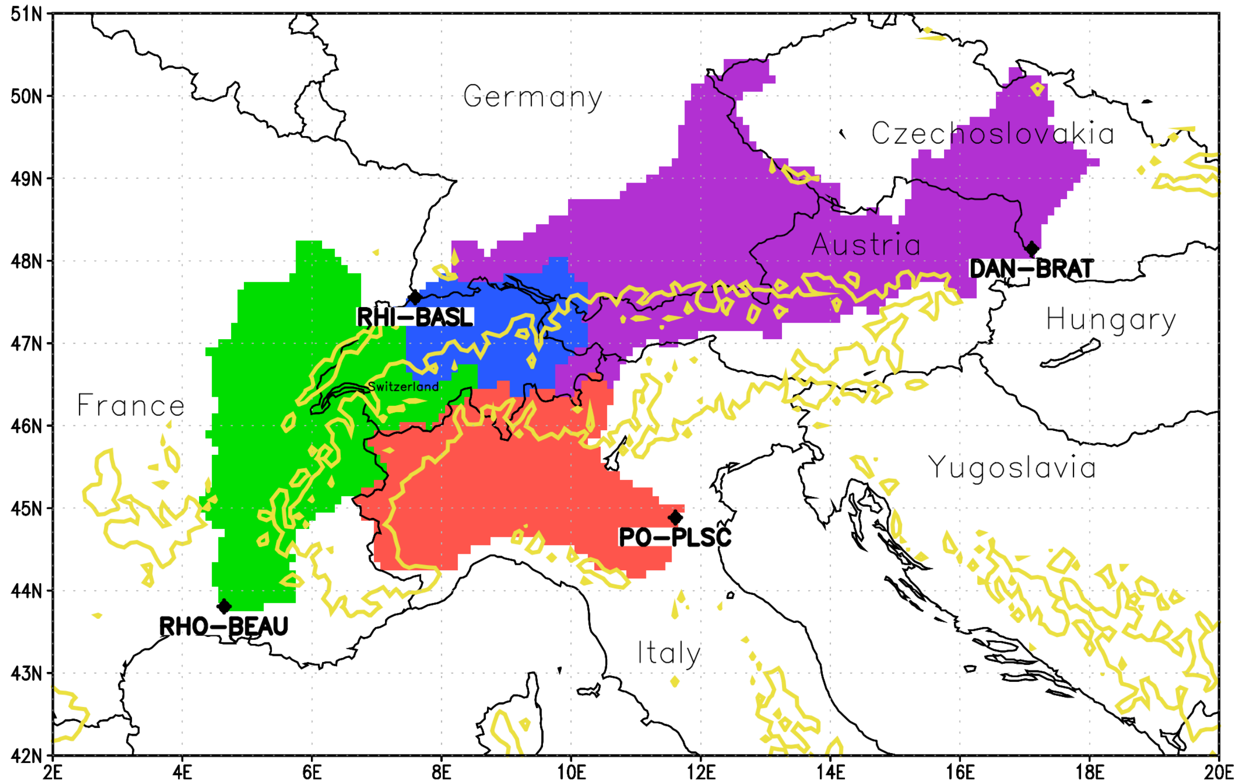

FIG. 1. Distribution of the four river discharge measurement sites (black diamonds) and the four contributing basins: the Rhine river in Basel (RHI-BASL, 7.59E-47.55N, in blue), the Danube river in Bratislava (DAN-BRAT, 17.11E-48.14N, in violet), the Rhone river in Beaucaire (RHO-BEAU, 4.64E-43.81N, in green) and the Po river in Pontelagoscuro (PO-PLSC, 11.60E-44.89N, in red). The basin delineations are generated using a 5' (about 5 to 6 km) river direction dataset (Graham et al. 1999), and

remapped at 10' resolution, consistent with the resolution of the climatic data used in this study. The yellow contour line depicts the 1000 m altitude of the orography.

Figure 1 shows the geographical distribution of the four discharge measurement sites and the contributing river basins, covering most of the Alps. From north to south and from west to east, they consist of the Rhine River in Basel (RHI-BASL, from 1869 to 2010), the Danube River in Bratislava (DAN-BRAT, from 1901 to 2007), the Rhone River in Beaucaire (RHO-BEAU, from 1921 to 2008), and the Po River in Pontelagoscuro (PO-PLSC, from 1831 to 2012). These datasets allowed us to distinguish between the long-term trend potentially linked to climate change and the effects associated with natural climate oscillations, which can determine the features of decadal variability, especially on the regional scale (Zampieri et al. 2013).

2.2. *Climate data*

In order to analyse the sensitivity of spring river discharge on climate trend and variability , we used gridded datasets of monthly homogenised surface observations from the HISTALP project. The data were made available at 10' resolution from 1801 to 2003 for precipitation, and from 1780 to 2008 for temperature (Efthymiadis et al. 2006, Auer *et al*., 2007, Brunetti et al. 2009) in the Alpine region (4-19E,43-49N). These data include all basins in full, with the exception of the Danube, where a small area located in the north of the region is not covered. We also downloaded and analysed a reconstruction of solid precipitation (i.e. snowfall). This reconstruction was produced by applying a statistical technique on the HISTALP temperature and total precipitation using snowfall data taken from direct observations in Austria, on the north-eastern side of the Alps (Chimani et al. 2011). This snowfall data was validated by Zampieri et al. (2013) in other regions of the Alps as well. Finally, we computed the snowmelt, replicating the procedure of van der Schrier et al. (2007), which parameterised snowmelt using a minimalistic model based on the amount of accumulated snow and on the mean monthly temperature.

To strengthen our results on the precipitation timings, we integrated the analysis of total precipitation using the global gridded observations from the Climate Research Unit (CRU) TS 3.10.01 dataset for the period 1901-2009. This was available at a resolution of 0.5 by 0.5 degrees (Mitchell and Jones 2005). As an independent dataset, we adopted the corresponding product from the 20th Century Reanalysis

Version 2, available from 1871 to present, at 2º spatial resolution (Compo et al. 2011). The results obtained with these datasets were compared to those of HISTALP during the overlapping period.

2.3. *Determination of discharge, precipitation and snowmelt peak timings*

In order to obtain a fine-scale estimate of the peak timings from the monthly discharge values, we fitted each annual cycle with analytical parametric functions as in Eq. (1).

$$(1) \quad D(y,m) = a_1(y)e^{(\frac{m-m_1(y)}{b_1(y)})^2} + d(y)$$

Eq. (1) represents our model for the discharge seasonal cycle *D(m,y)*, where *y* represents the year and *m* the time of the year expressed in months. In (1) the a_1 parameter represents the amplitude of the peak, m_1 represents the timing of the peak (not necessarily an integer), b_y is the spread of the discharge over time and *d* the minimum flow value. We chose a Gaussian function because it resembles the seasonal cycles of the Rhine and Danube River discharges, characterized by one summer peak. For the Po River, where there are peaks in both spring and autumn, we used a bigaussian function (i.e. a linear superposition of two Gaussians), as represented by Eq (2).

$$(2) \quad D(y,m) = a_1(y)e^{(\frac{m-m_1(y)}{b_1(y)})^2} + a_2(y)e^{(\frac{m-m_2(y)}{b_2(y)})^2} + d(y)$$

In Eq. (2), the second Gaussian is defined by a_2, m_2 and b_2, equivalent to the parameters in Eq (1). For the Rhone discharge, which does not have a winter minimum, we also used a bigaussian function, but with a linear interpolation of the values between the autumn and spring peaks.

For each year, we adopted a recursive procedure that defines the parameters, minimising the root mean square error (RMSE) between the observations and the analytical functions. Starting with a realistic guess of the parameters' values, the algorithm minimises the RMSE by increasing or decreasing each parameter with a prescribed increment. After a preliminary set of parameters is found, the procedure is repeated, decreasing these increments till the optimal estimate of the parameters is obtained. The final and the smallest increment for the Gaussian centres is 2 days. In this way, we produced the time-series of annual peak timings m_1 with sufficient accuracy to compute long-term trends and investigate decadal variability. We controlled the convergence of the algorithm by using different initial values for the parameters. This methodology is consistent with, but more accurate than, simply picking the month of maximum discharge.

Moreover, it allows the timing to be estimated even when the winter minimum is not pronounced, as in the case of the Rhone.

The same procedure was applied to determine the timings of precipitation, rainfall and snowmelt peaks. In addition to this, we characterised the shift towards earlier precipitation in HISTALP and the other datasets by computing the difference between the spring and winter averages.

2.4. Meta-analysis of the climatic effects on spring discharge timings

$$(3) \quad D(t) = \int^{A} R(x, y, t - \Delta t_{river}(x, y, t))dxdy$$

Assuming null hydrodynamic dispersion (Mesa and Mifflin, 1986), equation 3 represents the instantaneous discharge (D) at the measurement site. D is equal to the spatial integral over the contributing catchment area (A) of the runoff (R) at the time it was generated (t-Δt_{river}) in the location ($x,y \in A$). The delay between runoff generation in the basin and the river discharge recorded at the station (Δt_{river}) depends on the location and time. In fact, Δt_{river} is a function of the flow velocity along the channels from each point in the basin and the measurement site, and the distance. It includes the effects of buffering basins and water management. The distances do not change, unless there are diversions and other modifications in the river network structure and basin morphology during the period being considered, which could be the case in the Alpine basins over the past 100 years. In Eq. 3, the dependence on time of Δt_{river} is determined by the varying flow velocity. The velocity is a function of slope, river geometry and discharge. However, it is often approximated to a constant <1m/s in large-scale applications (Swensson et al. 2012). Therefore, all runoff generated in the Alpine basins would reach the measurement sites in a few days. Natural lakes (mostly managed) and artificial reservoirs that might be present in the river network can introduce an additional delay in the peak timing of up to a month or more (Haddeland et al., 2006, Hanasaki et al., 2006). The variability of this effect is largely unknown. But we provide a heuristic and qualitative characterisation of the relative importance of this effect on spring river discharge with respect to the natural drivers of variability.

Unfortunately, runoff measurements do not exist. Therefore, land surface processes, which generate runoff, need to be taken into account.

$$(4) \quad R(t) = R_{surf}(t) + R_{sub}(t)$$

Equation 4 states that the runoff exiting the soil is given by the superposition of two different sources: the runoff generated at the soil surface (R_{surf}) and the runoff generated by water that percolated into the soil, reaching the groundwater and recharging the river (R_{sub}).

$$(5) \quad R_{surf}(t) = (P_{liq}(t) + S_{melt}(t))(1 - I(t))$$

Surface runoff is given, in Eq. 5, by the amount of liquid water input to the soil coming from precipitation (P_{liq}) plus snowmelt (S_{melt}). Both of them are multiplied by the fraction that cannot enter the soil because of saturation and infiltration excess, which depends on the type of soil, on soil moisture, soil ice, and on precipitation intensity. In Eq.5, I represents the fraction of water that can infiltrate the soil. Subsurface runoff takes a complicated form involving evapotraspiration, Richards' equation for unsaturated soils and Darcy's law for saturated soils (Chow et al. 1988). The amount of liquid water that infiltrates and does not evaporate, and is not absorbed by plant roots, needs to percolate through the soil and interact with groundwater or sub-surface water flow before eventually reaching the river network. The percolation time is relatively short, in the order of a few days in shallow soils over steep topography. However, percolation can be delayed (or stopped) if the soil is too dry. This does not occur often in winter and spring in our region of interest. The timing of the interactions of soil moisture with groundwater and its variability are largely unknown (Zampieri et al. 2012). But the groundwater effect is presumably negligible over the steep slopes of the Alps, where most of the precipitation originates and is quickly converted into river discharge. Moreover, to our knowledge, no study has reported that groundwater is a major influence in determining the spring peaks of the rivers we studied. Finally, snowmelt timing depends mainly on snow albedo, temperature, and the liquid precipitation above the snowpack, and is limited by the previous snowfall (solid precipitation).

In the absence of snow and of the other non-linear soil processes and neglecting the anthropic influence, Eq. (1) would be time invariant, i.e. the timing of discharge at the measurement site would be driven just by timing of precipitation in the basin. Therefore, precipitation timing is the main climatic factor that we examine in this paper. On the other hand, if only snow is present, the timing of the river discharge peak would depend only on snowmelt timing. In fact, the system of equations (3), (4) and (5) can be solved analytically in a simplified ideal framework (Molini et al., 2011) obtaining an explicit formulation for the timing of peak discharge on total precipitation and temperature. Molini et al. (2011) highlighted the role of temperature in determining snowmelt timing and the ratio of liquid to solid precipitation. An analytical solution is not possible when using real observations. However, we can take advantage of the homogeneous set of self-consistent HISTALP data for effective analysis, based on the relevant variables identified in this section. These are, namely, the timing of total precipitation and rainfall, and the timing of snowmelt computed with the procedure explained in section 2.3. By analogy, and for comparison with the previous studies conducted in the U.S. and the few studies for the Alps that we cited in Section 1, we analysed the seasonal averages of these variables as well. In particular, we considered the spring averages of the rainfall to total precipitation ratio, and the rainfall to snowmelt ratio. This is equivalent to assuming the snow-melting takes place in spring. The rainfall to snowmelt ratio is of interest *per se* for flood risk assessments (Eckhardt and Ulbrich 2003, Dobler et al. 2012). The impact of human activities on spring peak discharge timings will be discussed only qualitatively in section 4.

2.5. *Determination of climatic effects on peak timings*

Given the large uncertainties of the physical processes and of the observations, we kept our analysis at a basic level, We analysed the linear trends of the peak discharge timings and of the relevant climatic variables identified in section 2.4, and we estimated their influence on the timing of peak river discharge through linear regressions. In this way, we could assess the sensitivity of spring river discharges on the relevant climatic variables.

Trends and linear regressions were computed with the standard least square method, using the "lm" functions available in the "R Software" (Wilkinson and Rogers 1973, Chambers 1992), which assumes that the residuals are independent of time and normally distributed with zero mean and constant variance. We checked these assumptions by examining regularly the residual and the q-q plots after each regression was computed. Linear regressions were also computed on time-series obtained by subtracting the linear trend from the original data. This ensured that the statistically significant relationships between the spring discharge timings and the other variables were consistent in determining the decadal climatic fluctuations, independently from the long-term trend. We averaged the relevant climatic variables over the basins before performing these computations. This was equivalent to neglecting the intra-basin differences in the delays connected to the river transport (Eq .3, section 2.3), which could generate an additional level of uncertainty in our results.

In order to facilitate the visual inspection of the plots, we removed the high-frequency noise by applying a running mean smoothing filter on an 11 years time window. This period was chosen to facilitate the interpretation of the results in terms of decadal (low-frequency) variability.

3. Results

3.1. *Seasonal cycles of river discharge, precipitation and snowmelt averaged over the Alpine basins.*

Figure 2: climatological seasonal cycles

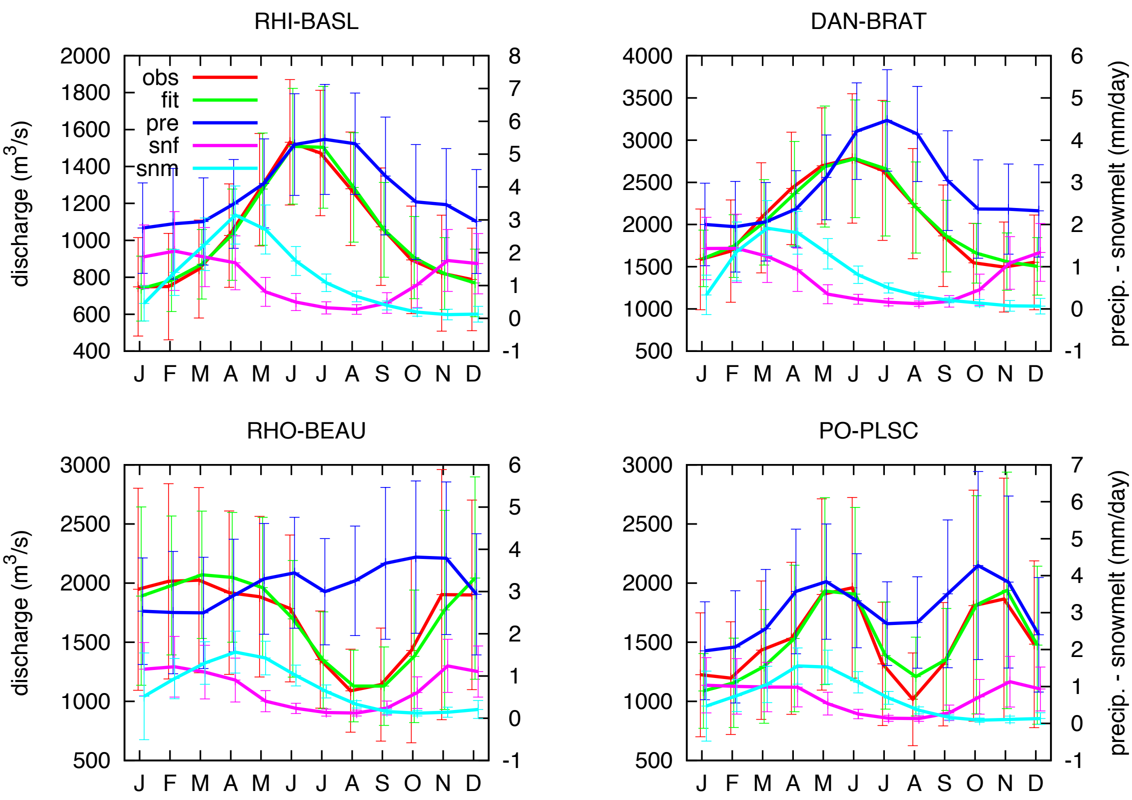

FIG. 2. Long-term mean seasonal cycles of the monthly river discharge from the observations and from the analytical fitting functions ('obs' in red and 'fit' in green, respectively, in m^3/s) and the HISTALP total precipitation, snowfall and snowmelt ('pre' in blue, 'snf' in violet, and 'snm' in cyan, respectively, in mm/day) averaged over the basins for RHI-BASL (top left panel), DAN-BRAT (top-right panel) the RHO-BEAU (bottom left panel) and PO-PLSC (bottom right panel), in m3/s. The error bars represent the standard deviations related to the interannual variability.

Figure 2 shows the climatological seasonal cycles of the rivers discharge from the observations and from the fitting functions. The peak discharges of the Rhine and Danube Rivers occur in summer, and they are captured by the fitting functions. The fitting function reproduces the spring and autumn peaks that characterise the Po River discharge, but it overestimates the low-flow in summer. The Rhone River also displays a late summer minimum, but an approximately constant discharge in the winter and spring seasons. Also here, the fitting function performs reasonably well. In general, the fitting functions underestimate the winter interannual variability.

Figure 2 also shows the mean seasonal cycles of the HISTALP precipitation averaged over the basins. On the northern flanks of the Alps the peaks occur in summer, consistent with the single peak discharge in RHI-BEAU and DAN-BRAT. The discharge peaks come earlier than the precipitation peaks. This indicates a contribution from the runoff generated earlier, presumably from snowmelt, and it is confirmed by the amount and timing of snowfall and snowmelt plotted in Figure 2.

The precipitation time-series on the southern flank of the Alps show a summer minimum. The double peak distribution of the Po River is due to a mixture of snowmelt and rainfall in spring, but only to rainfall in autumn. This is partly true also for RHO-BEAU, where the total precipitation minimum in winter is less marked. The snow melting annual cycle has a similar shape in all basins, but different timings and a different relative intensity with respect to precipitation. It peaks in March in the Danube basin, and between April and May in the other basins. Therefore, spring averages of the relevant climatic variables should be able to capture the processes affecting snowmelt in all basins. The fitting procedures implemented in order to determine the timings of precipitation and snowmelt perform equally well as those for discharge (not shown).

Similar results for the precipitation climatologies can be obtained using the CRU gridded observations and the 20th Century Reanalyses (not shown), which include the whole Danube basin. The 20th Century Reanalyses product displays less inter-basin differences than the other datasets, most likely because of its lower resolution.

3.2. *Trend, variability of river discharge timing and of relevant climatic variables.*

Figure 3: discharge timings and climatic data time-series

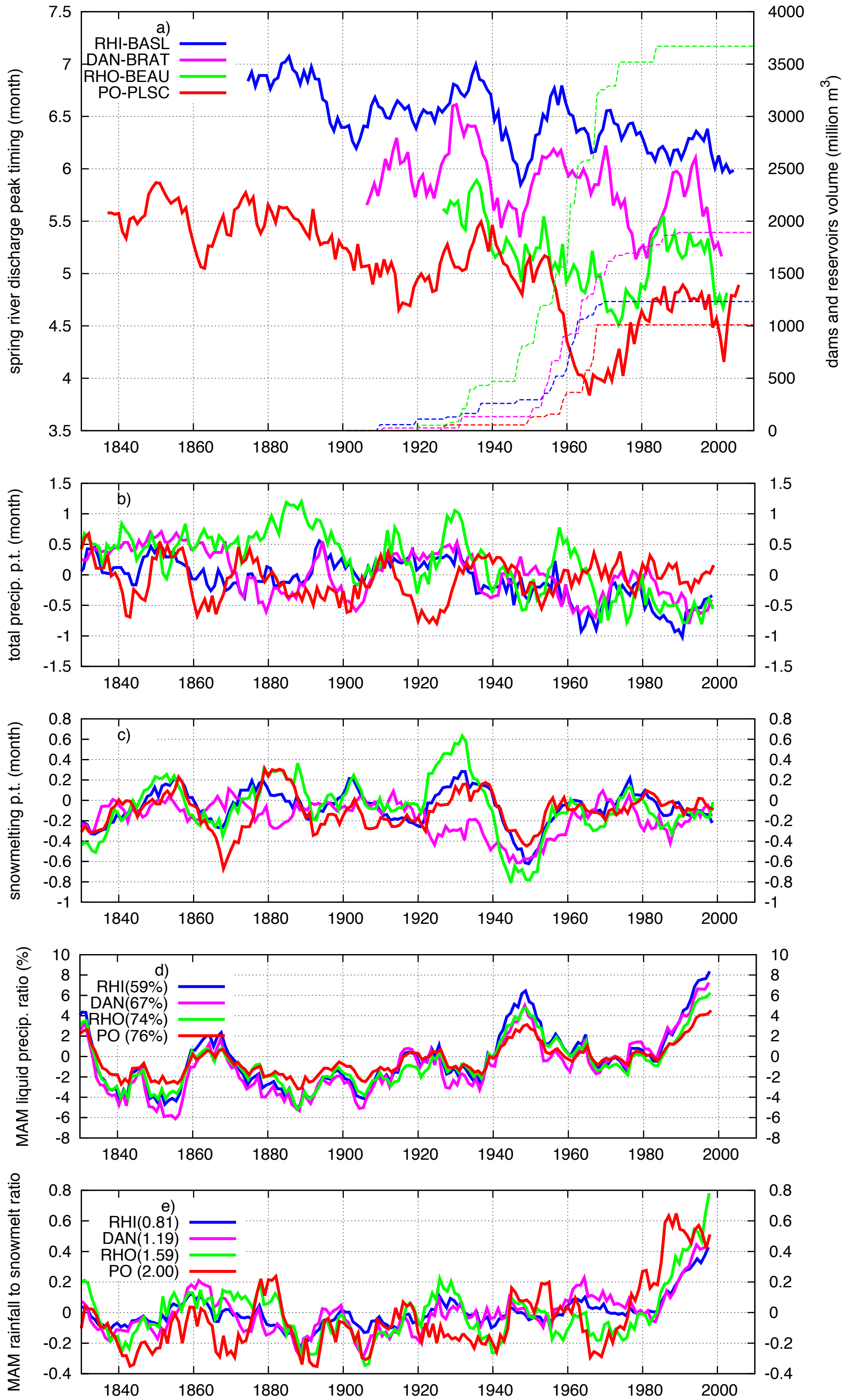

FIG. 3. 11-year running mean time-series of: a) river discharge, b) total precipitation and c) snowmelt peak timings (in months). 11-year running mean time-series of: d) mean spring liquid (rainfall) to total precipitation ratio (in %), and e) mean spring rainfall to snowmelt ratio (adimensional) for each river. All data but the river discharge timings are averaged over the basins displayed in Figure 1 and plotted as anomalies with respect to the long-term climatology. Climatological values for spring rainfall to total precipitation ratio and rainfall to snowmelt ratio, which cannot be deduced from Fig. 1, are listed in the legends of the corresponding plots. Dashed lines on panel a) represent the accumulated dam and managed

reservoirs volume in the basins upstream of the measurement sites. These were computed using the Global Reservoir and Dam (GRanD) database (Lehner et al. 2011).

Figure 3 shows the river discharge peak timings time-series obtained from the fitting functions. The main finding is a clear tendency for earlier peaks. In general, discharge peak timings are subject to an earlier trend of more than two weeks per century on the northern flank of the Alps, and more than 3 weeks on the southern flank. The linear trend results are listed in Table 1. Importantly, all the computed trends are statistically significant at 99.9% ($p < 0.001$).

The time-series shown in Figure 3 exhibit similar features of low-frequency variability among the rivers. However, the Po River displays a marked and prolonged period of earlier discharges around the 1970s and then a recovery of the climatological conditions in the 1990s, which is not present in the time-series of the other three rivers.

We plot in Figure 3 the time-series of total precipitation and snowmelt peak timings, and the spring averages of liquid to total precipitation ratio, and of the rainfall to snowmelt ratio, averaged over the basins. Most of these variables, including the liquid portion of total precipitation, display significant trends that are quantified and listed in Table 1. Total precipitation and, to a lesser extent, rainfall, are characterised by a tendency towards earlier peaks that is consistent with the trend of the river discharge peak timings for all the basins except the Po.

Snowmelt is characterised by a relatively small but significant trend towards earlier peaks. The mean spring percentage of liquid precipitation time-series (Figure 3, panel d) displays a significantly increasing trend in all basins, of about 4.5% per century in the northern basins, 3.5% in the Rhone basin and 2.5% in the Po basin. These trends are consistent with the warming of the Alpine region that has been observed during the same period (see spring temperature trend in Table 1).

As an index to characterise the pluvial vs. nival river regime, we compute the rainfall to snowmelt ratio in the basins. The corresponding time-series are displayed in the bottom panel of Figure 3. In all the cases considered, the index appears to be approximately stationary till the 1970s-80s and then displays a marked trend towards a more pluvial-torrential regime (see also the corresponding overall positive trend in

Table 1). Interestingly, this shift occurs about 10 years earlier in the Po basin compared to the other river basins.

3.3. *Sensitivity of peak discharge timings on the relevant climatic variables.*

Table 2 shows the results of this linear regression analysis computed over all the overlapping periods shown in Figures 3 and 4. Total precipitation and, to a lesser extent, rainfall, in some cases correlate with the river discharge peak timings. However, the results are not statistically significant if we remove the trend (the trend values are displayed in Table 1). Therefore, it seems they are not influencing the low-frequency fluctuations of spring discharge, at least according to the datasets we used. We will provide in section 3.4 an independent estimate of this counterintuitive result.

Snowmelt seems to have a major role in determining the low frequency variability of the discharge timing. This effect is quantified by the linear regression results computed on the detrended snowmelt and river discharge time-series, showing that a hypothetical earlier discharge of 1 day in snowmelt timing is likely to be followed by an advance of up to half a day in the discharge peaks (see Table 2). The impact of snowmelt on the river peak timings is especially important for the Rhine. By comparing the snowmelt time-series with the spring discharge plotted in Figure 3, we note a clear connection between them for most rivers/basins around 1950, when snowmelt was probably determining the observed period of earlier discharge.

The mean spring percentage of liquid precipitation time-series are negatively correlated with respect to the low-frequency fluctuations of the discharge timing in the Rhine and Danube Rivers, where for each percentage increase in this ratio we expect a 1 day advance in the corresponding river discharge (see results in Table 2). This is consistent with the fact that the more spring precipitation falls as rainfall the more the river discharge is brought forward. This very likely explains a large portion of variability in the earlier discharge periods that occurred in the 1860s and in the 1940s.

We did not find significant correlations of the rainfall to snowmelt ratio with the discharge timing time-series.

3.4. *Spring vs. winter precipitation.*

We provide further support for the result on the earlier spring precipitation by including the analysis of the CRU TS 3.10.01 and of the 20th Century Reanalysis products.

Figure 4: precipitation seasonality time-series: winter, spring and spring minus winter

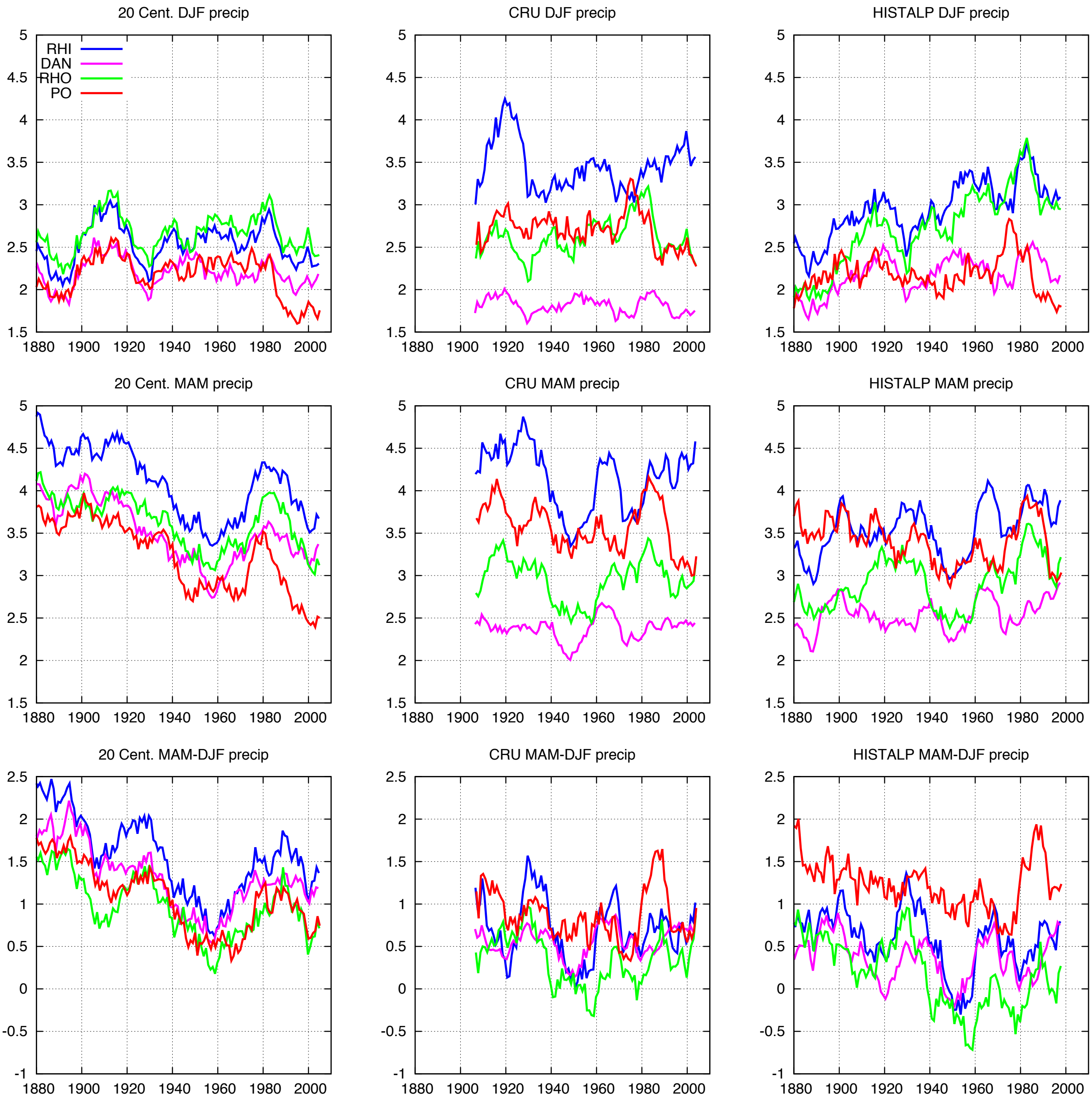

FIG. 4. Winter (DJF) and spring (MAM) total precipitation time-series averaged in the four river basins and the difference between them computed on the 20th Century Reanalysis, CRU TS 3.10.01 and HISTALP.

The change in precipitation seasonality can be assessed on the time-series of the seasonal means averaged over the basins, which are plotted in Figure 4. We note a large inconsistency in the individual winter and spring signals obtained from the different datasets (top and central panels), which is evident in terms of mean values, of trends (see also Table 1), and of low-frequency fluctuations. In this respect, the gridded observations (CRU and HISTALP) appear to be in slightly better agreement compared to the reanalysis product. The Reanalysis shows a significant decreasing precipitation trend over all basins. The spring trend appears to be substantially larger than the slightly negative winter trend. As a consequence, the proportion of winter to spring precipitation increases over a large part of the Alpine region.

CRU and HISTALP seem to capture better the inter-basin differences, probably because of the higher resolution with respect to the Reanalysis. However, their seasonal means are quite diverse and they show completely different trends between themselves and also with respect to the Reanalysis.

On the other hand, the time-series of the difference between spring and winter precipitation means seem to be more consistent among all datasets, which show closer mean values and comparable features of decadal variability as well. Also, the trends are more consistent between the datasets. In fact, the proportion of winter to spring precipitation increases over all basins in all datasets. CRU shows less statistically significant results. In the case of CRU, however, it should be kept in mind that the trend has been computed from data covering a shorter and more recent time period, when the negative trend is also less evident also in the other data sets.

A large delay (i.e. more spring versus winter precipitation) occurred in the Po basin over the last 20 years and it is consistent with the Po discharge timings in Pontelagoscuro (Figure 3, top panel). Similar delays also took place in the Rhine, the Rhone and the Danube basins, but with different timings.

The consistency of the spring minus winter precipitation time-series with the variations that we observed in the spring river discharge, both in terms of trend and of low frequency fluctuations, are also supported by the results of the linear regression listed in Table 2. With a few exceptions, the shift towards winter precipitation is well correlated to the river discharge timing variations, both in terms of trend and of low frequency modulations. The biggest impact is found in the Po basin, where an increase of winter precipitation of 1 mm/day with respect to the spring amount can explain an earlier river discharge of more than 2 weeks.

4. Discussion

The results of this study indicate that changes in the seasonality of total precipitation can significantly affect the hydrological cycle of the Alpine region. Our analysis is consistent with previous studies focused on the determination of the monthly and seasonal discharge trends (Pfister et al., 2006, Birsan et al. 2005, Stahl et al. 2010), which found a tendency of increasing winter runoff with respect to other seasons. Compared to Bard et al. (2012), who explicitly analyse the timing of the spring discharge for the last 40 years, we have undertaken a more extended study that allowed us to separate the long-term trend from the decadal variability. In our analysis, the long-term trend of earlier spring river discharge timings is mostly explained by the change of seasonality of precipitation and the increase of its liquid portion, while snowmelt is better at explaining the low-frequency (decadal) fluctuations. This peculiarity of the Alpine climate change highlighted in our study differs from the common perception that earlier spring discharges are mainly due to earlier snowmelt, and to the larger ratio of rainfall to total precipitation caused by global warming (see e.g. Aguado et al. 1992, Dettinger and Cayan 1995 Cayan et al. 2001, Barnett et al. 2005, Moore et al. 2007, Pederson et al. 2011). An interesting field of further research would be an analysis of the links between precipitation and snowmelt seasonality and the spring runoff timing in the climate models, including the projected changes for the future climate change scenarios.

A limitation of our analysis is that we neglect soil moisture and groundwater processes (Tague and Grant, 2009, Mayer and Naman 2011) and glacier ice melting (Kaser et al. 2010), because of the lack of observed data at the scales we are considering here. However, as the cited papers state, these aspects are only minor influences on the processes leading to the peak discharge maximum. Black carbon deposition over the snowpack, decreasing albedo, can also accelerate the snowmelt (Flanner et al. 2009). In fact, the period of maximum carbonate particle deposition in the Alps (Thevenon et al. 2009, Fagerli et al. 2007, Legrand et al. 2007) is consistent with the recent advance in the Po river spring discharge. However, this effect cannot be detected in the data we used. Finally, the intensive water management in the region might affect river discharge. This effect is difficult to quantify. But in Figure 3 we provide the basins' estimates of the accumulated dam and reservoir volumes (thin dashed lines), which are known to delay the peak discharge and to reduce the interannual variability (Haddeland et al. 2006). In all basins, most of the hydraulic structures were built around the 1960s, but they do not appear to affect significantly the trend and the low-frequency variability of the spring peak timings. Moreover, it is unlikely that human modification of land and hydrology could produce the common features that we found in the different basins, which are regulated by different authorities and presumably subject to different land-use and water management practices. Therefore, we think that most of the signals that we have detected and discussed in this study are due to climate variability and change.

The consistency of the regional-scale trend estimate from observations, reanalysis and models remains an issue of debate (Stott et al. 2010). The instrumental observations are affected by missing periods and in-homogeneities because of non-climatic factors and, in fact, algorithms are developed to correct the station data from these effects and increase the reliability of the computed trends (e.g Williams et al. 2012, Venema et al. 2012 and references therein). It is noteworthy, however, that the HISTALP dataset accounts for some of these correction methods. On the other hand, reanalysis products, which combine modelled and observed climate signals in a dynamical coherent way, are also affected by observational errors, spatial and temporal in-homogeneities in the observational system, model errors, and errors arising through the choice of methodology that might even more severely affect the trend computation (Bengtsson et al. 2004, Sterl 2004, Thorne and Vose 2010).

As a contingent result of this study, we found that computing a differential trend between two seasonal means seems to reduce some of the problems, emphasising the consistent aspects that emerge from a comparison between trends computed from different sources. Presumably, computing the difference of two seasonal means removes the in-homogeneities and biases that affect the two time-series in the same way. Therefore, our analysis of spring discharge timings estimated from the fitting functions, which implicitly accounts for the monthly values as weights, can be supported by similar arguments. Finally, we stress the importance of adopting alternative metrics to better analyse the climatic variables and their changes in terms of seasonality, i.e. amplitude, timing and duration that characterise the seasonal cycles, as, for instance, in Feng et al. (2013).

5. Conclusions

We found a consistent earlier spring discharge of more than two weeks per century in the basins located north of the Alps (Rhine and Danube), and more than three weeks per century in the basins located to the south (Rhone and Po). In the Po basin, a significant role in this earlier trend is also played by the long-term tendency of an increased spring liquid precipitation ratio, in line with the general warming trend observed over the Alpine region (Serquet et al. 2011, Beniston 2012). The low-frequency (decadal) fluctuations of spring discharge timings can be partly explained by changes in the snowmelt timings, especially in the Rhine and Po basins, and partly by changes in the liquid precipitation ratio in all basins except the Rhone and the Po. We detected a recent shift towards a pluvial-torrential regime with respect to the snowmelt-dominated regime that has characterised the southern basins since the 1970s and the northern basins since the 1980s. These changes can amplify the flood risk (Eckhardt and Ulbrich 2003, Dobler et al. 2012) and partially explain the earlier discharges that we found in the 1960s. Finally, we found consistent changes in some aspects of the precipitation seasonality that probably drive much of the long-term trend and the low-frequency fluctuations of spring discharge timings. Interestingly, our analysis of the difference between the spring and winter precipitation improves the consistency of the results when different independent datasets are compared.

Acknowledgments. The research leading to these results has received funding from the Italian Ministry of Education, University and Research and the Italian Ministry of Environment, Land and Sea under the GEMINA and NEXTDATA projects. This work also contributes to the HyMex Programme. We are indebted to Prof. Cintia Bertacchi Uvo and Dr. Sandro Nanni for the provision of some of the river discharge data that were not included in GRDC. In this study, trends and linear regressions are computed using the "R" software (www.r-project.org)

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